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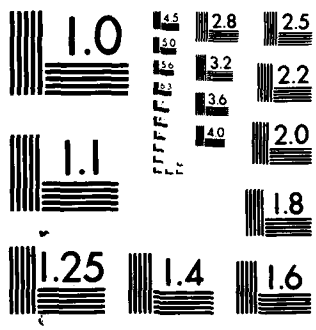

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15 October 1979

FINAL REPORT F/409-4-30

METRIC ACCURACY ANALYSIS

FOR THE PERIOD

1 OCTOBER 1978 THROUGH 30 SEPTEMBER 1979

C. R. Pedersen

Prepared by

Riverside Research Institute
80 West End Avenue
New York, ~~N.Y.~~ 10023

Prepared for

Massachusetts Institute of Technology
Lincoln Laboratory

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Raymond L. Loiselle

Raymond L. Loiselle, Lt. Col., USAF
Chief, ESD Lincoln Laboratory Project Office

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During the contract year 1 October 1978 through 30 September 1979 considerable progress was made toward implementing a new Lincoln Orbit Determination (LODE) software capability at MIT Lincoln Laboratory for precise post-mission determination of reentry vehicle trajectory and motions during both exo- and endo-atmospheric phases of flight. Early in the year, RRI completed preparation of all equations for the Kalman-based forward-backward filter-smoother algorithm which provides the optimal LODE estimation capability.

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Instructions for programming these equations were prepared on detailed Hierarchical-Input-Process-Output (HIPO) format and were delivered to MIT/LL for coding, verification. and validation. At year end the equations have been coded,and code debugging and numerical equation verification are in progress, with completion planned for calendar 1980.

AUTHORIZATION

This report describes research performed at Riverside Research Institute, with principal technical contributions by D.M. Leskiw, K. S. Miller, C. R. Pedersen, and M. M. Rochwarger.

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I. Weissman
Research Director
Advanced Technology Division

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ABSTRACT

During the contract year 1 October 1978 through 30 September 1979 considerable progress was made toward implementing a new Lincoln Orbit Determination (LODE) software capability at MIT Lincoln Laboratory for precise post-mission determination of reentry vehicle trajectory and motions during both exo- and endo-atmospheric phases of the flight. Early in the year, RRI completed preparation of all equations for the Kalman-based forward-backward filter-smoother algorithm which provides the optimal LODE estimation capability. Instructions for programming these equations were prepared in detailed Hierarchical-Input-Process-Output (HIPO) format and were delivered to MIT/LL for coding, verification, and validation. At year end, the equations have been coded,and code debugging and numerical equation verification are in progress, with completion planned for calendar 1980.

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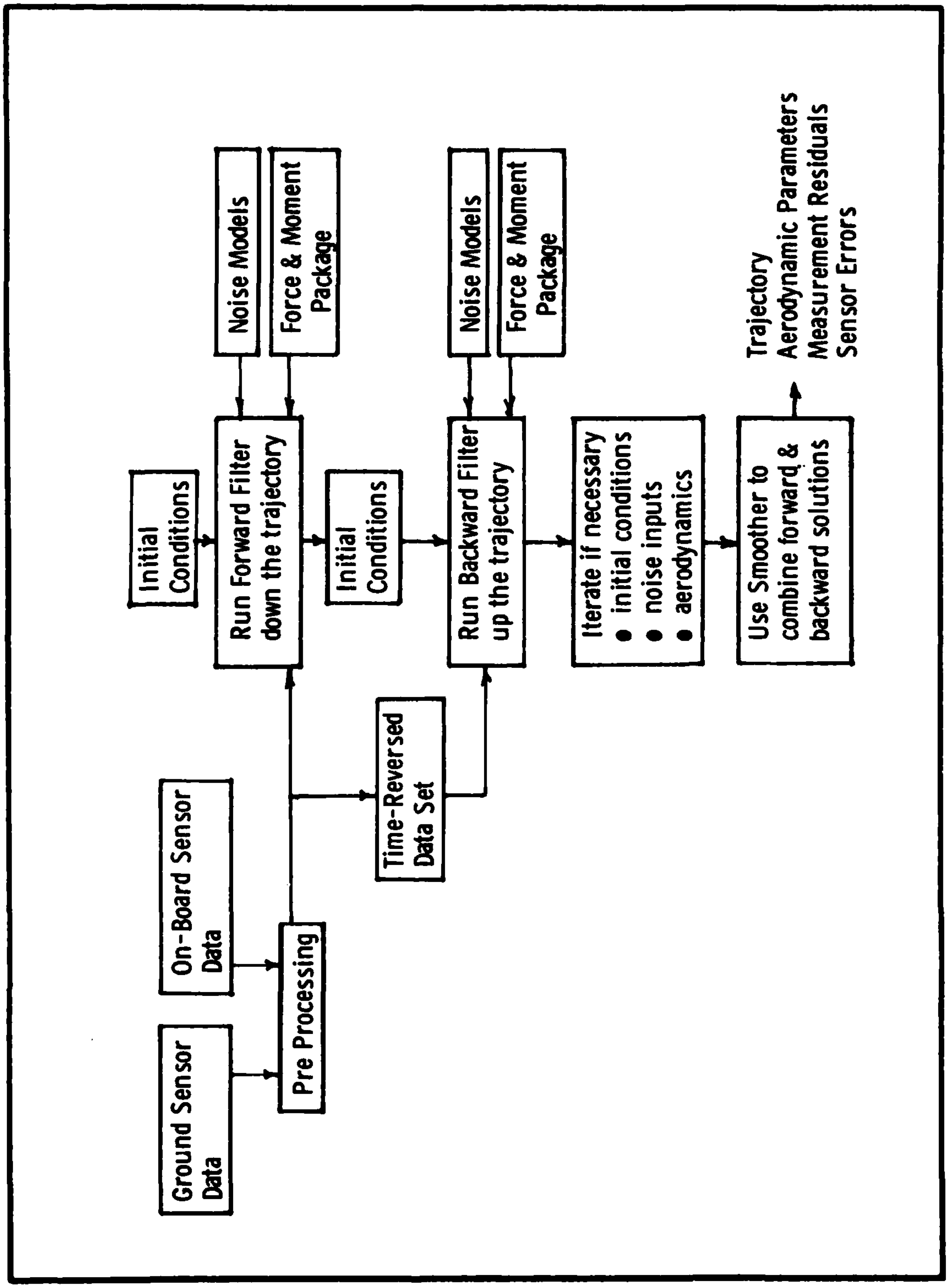
I. INTRODUCTION

This report summarizes activities and accomplishments by Riverside Research Institute (RRI) in performing metric accuracy analyses for MIT Lincoln Laboratory (MIT/LL) from 1 October 1978 through 30 September 1979. The reporting period covers an intermediate phase in the development of the new LODE* post-mission trajectory estimation software system for MIT/LL, and coincides largely with the coding implementation at MIT/LL of equations previously formulated by RRI[1]. Detailed debugging and testing is in progress at the close of the period while system validation and detailed documentation are scheduled later, for calendar 1980.[2]

The purpose of this report is, therefore, to present an overview of status and accomplishment to date. The archival function of documenting detailed technical results, however, will be accomplished as part of the equation and software documentation scheduled for calendar year 1980.

The technical goal for LODE during 1979 has remained the same as that originally recommended by RRI,[3] namely implementation of a Kalman-based forward-backward-smoother algorithm which is optimized for accurate estimation in the intended non-real-time post-mission application at MIT/LL. The functional application of this algorithm is shown in skeleton form in Figure I-1.

*Lincoln Orbit Determination



F/409-4-30 FIG. I-1 OVERVIEW OF LODE POST MISSION PROCEDURE

The key elements in the concept are the forward and backward filters, which accept measurement data and produce estimates of the trajectory state vector, and the smoother, which optimally combines the forward and backward trajectory estimates in order to produce the single best estimate of the trajectory which, at each point, is based on all of the measurement data.*

Ground and on-board measurement data are collected and preprocessed to provide clean, calibrated data for the filter inputs, and the forward and backward filter runs are iterated if necessary to permit adjustment of the initial conditions, the parameters of the measurement noise models, or the aerodynamic model which relates vehicle attitude and motion to aerodynamic forces and moments. The pre-processing procedures are the responsibility of MIT/LL staff while RRI has had responsibility for formulating the overall algorithm and deriving and specifying all equations for the two filters, the smoother, the measurement models for each sensor type (i.e., radar, optics, Multistatic Measurement System, system, on-board gyros, and on-board accelerometers), and the aerodynamic model (including angle-of-attack effects and vehicle mass and aerodynamic unbalance).

*Throughout, "optimal" and "best" are used to mean the smallest-variance estimate among all unbiased and locally linear estimates of the trajectory state vector.

II. STATUS AND ACHIEVEMENTS

The Metric Accuracy Analysis activity is a joint effort involving staff from RRI, MIT/LL, and Ford-Aerospace, with areas of principal responsibility as shown in Figure II-1. The status and achievements for each of the several RRI task areas will be summarized in separate paragraphs which follow. However the overall program status is as indicated in Figure II-1.

The preparation and verification of equations are essentially complete while the completion of HIPO* instructions for programming, to convey these equations to Ford-Aerospace programming staff, will be completed in 1980. Coding, debugging, and testing are in progress, and regular technical and software liaison meetings have taken place throughout the year and will continue. Performance evaluation is the overall responsibility of MIT/LL, with heavy involvement by both RRI and Ford-Aerospace, and will be completed in calendar 1980 when the overall LODE system (cf. Fig. I-1) has been debugged with simulated data and is running as a system. (Subsystem tests of the filter algorithm thus far have been successful and highly encouraging). Documentation will be assembled and published by MIT/LL in 1980 with major inputs from RRI as well as from Ford-Aerospace personnel.

The more detailed description of status in RRI's respective areas is provided in the following paragraphs, which in sequence and titling are keyed to the RRI proposal of activities for the year[4].

*Hierarchical Input-Process-Output

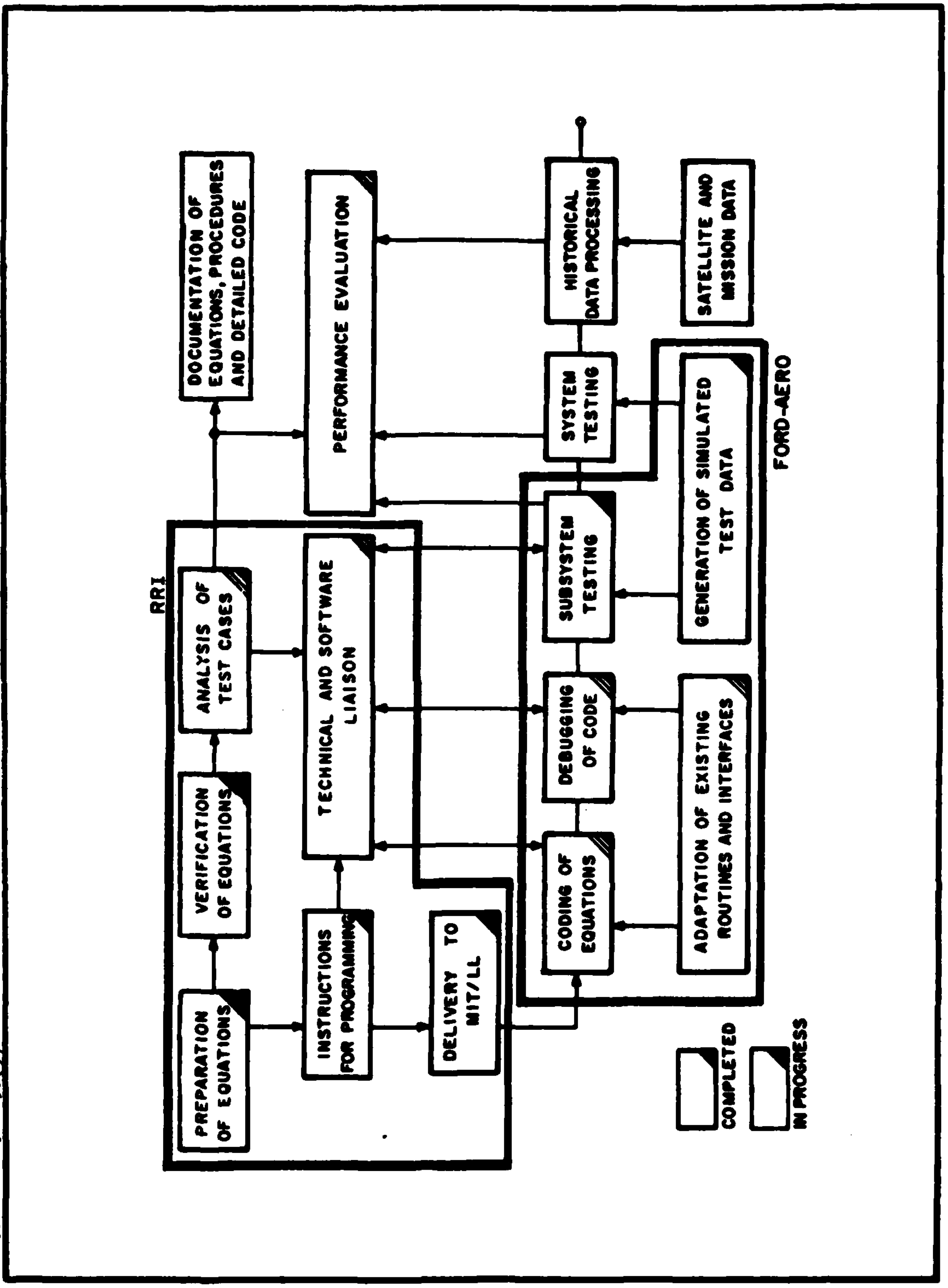


FIG. II -1 FUNCTIONAL OVERVIEW FOR METRIC ACCURACY ACTIVITIES

A. PREPARATION OF EQUATIONS

The derivation by RRI of detailed equations for the forward and backward Kalman filters and for the smoothing algorithm was essentially completed during the previous contract year. These equations provide for best estimation of metric trajectory information, ground and on-board sensor biases, and vehicle aerodynamic parameters, and include a full rigid-body motion solution for a spinning quasi-symmetric vehicle.

During the current contract year these equations were extended to provide for a generally asymmetric vehicle (that is, a vehicle whose aerodynamic and inertial properties are functions of roll angle), and to include mass-offset and trim-angle misalignments between the principal aerodynamic axes and the principal inertial axes. This model has sufficient generality to separately account for and estimate the principal physical origins of "roll-resonance" effects. With this extension to a general aerodynamic model, work on defining the equations for the LODE processor was complete.

In addition, a considerable effort during the year was devoted to careful derivations of alternative forms for several critical equations, in order to preserve their mathematical equivalence to the optimal solution but to enhance their tractability for computer implementation. The specific critical areas which may be mentioned in this respect are:

1. propagation of forward and backward covariance matrices, denoted P and Q respectively, for the filter state estimates,
2. determination of their inverses, P^{-1} and Q^{-1},
3. determination of the covariance matrix, M, for the smoothed estimate, where M is defined in terms of its inverse by

$$M^{-1} = P^{-1} + Q^{-1},$$

4. maintenance of accuracy in calculations involving widely disparate magnitudes.

From the outset RRI has recognized the undesirability of directly computing the three inverses* of very large matrices (order 100 or greater) which would be required for straightforward implementation of the smoothing algorithm in its most direct form[5]. Instead RRI has formulated the equations to provide for propagation of the respective inverse matrices directly, rather than propagation of the basic matrix followed by direct inversion. The evaluation of these alternative approaches has been accomplished through a combination of theoretical analysis (cf. section II-E, "Analysis of Test Cases") and application to simulated data as part of equation verification (cf. Section II-B,following, "Verification of Equations"). At the close of the contract period these evaluations were in progress. During preparation of this report these evaluations were largely completed. Only a definition of how best to proceed with the M matrix remained undecided and was approaching conclusion.

Three RRI contributions deserve separate note. First, the exactly optimal equations for combining forward and backward estimates in a smoother were derived during the year[6] and published[7]. These equations extended and clarified previous versions existent in the literature. Second, a reformulation[8] of the basic smoother equation led to a form which reduces by many orders of magnitude the sensitivity of the smoothed estimate to a required differencing of large numbers. Third, an exact algorithm[9] for inverting the sum of two matrices has been derived**

---

*P^{-1}, Q^{-1}, and $M = (M^{-1})^{-1}$.

**under separate auspices at RRI.

and is available should covariance-matrix inversion re-enter the picture. The two latter contributions have far-reaching impact for large-scale smoother implementations but, to date, neither has been found in the published literature.

B. VERIFICATION OF EQUATIONS

During the previous contract year the equations being derived by RRI were verified by being coded in a reduced form at RRI (the "proto program") and tested against simulated data and theoretical results. The purpose was to find and eliminate any analytical or algebraic errors by demonstrating working subsystem solutions before coding the full equations at MIT/LL and attempting to debug possibly invalid equations. During the previous year the equations for the forward filter were thus verified and instructions for programming were delivered to MIT/LL.

At the start of the current year (November 1978) instructions for programming the backward filter and the smoother were prepared and delivered to MIT/LL to be coded for verification of equations in concert with code debugging. Through this method critical equation areas were identified and RRI undertook to provide either improved equation approximations or more numerically tractable versions of exact equations,as appropriate. This working procedure continued iteratively during the year and came to include code checkout (by extension of the proto-program) at RRI and transfer of code to MIT/LL via punched cards and listings. Indicative of the analyses and activities which RRI performed to resolve difficulties in equation verification, are the following:

1. examination of first, second, third order matric Taylor series for covariance matrix propagation,
2. rearrangement and inclusion of terms in covariance equations in consistent increasing order of approximation,

3. examination of alternative and explicitly symmetric form for covariance update equation,
4. improved propagation accuracy through subdivision of the basic update time interval (0.1 s),
5. consideration of different integration schemes for covariance propagation by direct integration of the covariance differential equation,
6. adoption of the exact system transition matrix (computed from the matric exponential one-sided Green's function) for propagating covariance matrices,
7. incorporation of mid-point evaluation for transition matrices to locally symmetrize forward and backward propagation equations,
8. incorporation of new form of smoother equation (mentioned in Sec. II-A) to reduce sensitivity to errors in differences of large numbers.

This facet of the LODE implementation has been unexpectedly drawn out and has acted to delay delivery of instructions for programming the general aerodynamic model.

As of this writing the filter equations have been thoroughly investigated and equations for forward and backward filters may be set down with some confidence. The exponential form for the transition matrix for propagating the smoother covariance matrix has been verified and found to be acceptable when system noise is zero. However, this approximation has been found to be inadequate when system noise is present. The difficulty on the latter case was determined to be caused by the fact that the assumptions used in deriving the exponential form of the smoother transition matrix were violated when system noise is not zero. An alternative form for propagating M which does not rely on transition matrices is currently being investigated.

C. INSTRUCTIONS FOR PROGRAMMING

The improved programming technique called HIPO* had previously been recommended by RRI and accepted by MIT/LL as a suitable means for transferring a unique definition of LODE equations and algorithmic structure derived at RRI to MIT/LL for coding and debugging. Table II-1 shows the schedule of delivery and current status. Through an intensive effort from 5 April 1978 in the previous contract year to 22 March 1979 in the current year a set of HIPO was generated and delivered by RRI. This set (of about 250 pages) provides complete equations for LODE with only three exceptions.

First, equations for the general aerodynamic model have been derived at RRI but reduction to HIPO form remains to be done. Second, nose-tip range and range rate extensions to the measurement model remain to be derived. Similarly, and third, the estimation equations for (small) timing bias are planned for definition and phase-in in 1980.

In addition RRI has provided improved and revised covariance propagation and smoother equations to MIT/LL in the form of card decks and listings to reflect improvements discussed above in Section II-B. It is expected that replacement HIPO sheets will be provided to document these and any further equation or algorithm changes which may be necessary. Also, temporary resource constraints at RRI are requiring the delay of further effort on HIPO because of the higher priority which has been assigned to investigation of the smoother algorithm.

D. ANALYSIS OF TEST CASES

Several major different forms of test cases have been used to debug, verify, and checkout coded equations.

*Hierarchical Input-Process-Output

	5 April '78	6 November '78	20 November '78	18 December '78	18 January '79	2 March '79	22 March '79	STATUS
FORWARD KALMAN FILTER	X				X			X
SYSTEM MODEL	X					X		X
POINT MASS	X					X		X
GRAVITY MODEL	X					X		X
AERODYNAMIC MODEL	X					X		X
DRAG	X					X		X
LIFT	X					X		X
SIDE FORCE	X					X		X
RIGID BODY				X		X		X
EULER'S EQUATIONS				X		X		X
ASYMMETRIC AERODYNAMICS								(1)
SYMMETRIC AERODYNAMICS								(2)
MEASUREMENT MODEL	X				X			X
POINT MASS	X				X			X
MONOSTATIC SENSOR	X				X			X
AZIMUTH	X				X			X
ELEVATION	X				X			X
RANGE	X				X			X
RANGE RATE					X			X
AZ-EL CORRELATION					X			X
TRAVERSE BIAS					X			X
MULTISTATIC MEASUREMENT SYSTEM					X			X
MONOSTATIC SENSOR					X			X
RANGE DIFFERENCE					X			X
RANGE RATE SUM					X			X
RANGE-RANGE DIFFERENCE CORRELATION					X			X
RIGID BODY							X	X
MONOSTATIC SENSOR								(1)
RANGE (NOSE TIP)								(1)
RANGE RATE (NOSE TIP)								(1)
ON-BOARD ACCELEROMETER				X			X	X
ON BOARD ACCELEROMETER ERROR MODEL							X	X
ON-BOARD RATE GYRO							X	X
ON-BOARD RATE GYRO ERROR MODEL							X	X
DIRECT COHERENT PHASE	not planned for [illegible]							
TIMING BIASES								(3)
PROPAGATION EQUATIONS	X							X
STATE ESTIMATE	X							X
COVARIANCE MATRIX	X							X
UPDATE EQUATIONS	X				X			X
SCALAR MEASUREMENT MODEL	X				X			X
STATE ESTIMATE	X				X			X
COVARIANCE MATRIX	X				X			X
VECTOR MEASUREMENT MODEL					X			X
BACKWARD KALMAN FILTER		X						X
PROPAGATION EQUATIONS		X						X
STATE ESTIMATE		X						X
COVARIANCE MATRIX		X						X
SMOOTHER			X					X
PROPAGATION			X					X
COVARIANCE MATRIX			X					X
INVERSE COVARIANCE MATRIX			X					(4)
SMOOTHED COVARIANCE MATRIX			X					(4)
UPDATE ORTHOGONALITY	no longer needed							
COVARIANCE MATRIX	no longer needed							
INVERSE COVARIANCE MATRIX	no longer needed							
SMOOTHED STATE ESTIMATE			X					(4)

Notes: (1) completion planned in calendar 1980.
(2) subset of asymmetric aerodynamics
(3) capability to be phased in during calendar 1980.
(4) will require modification in calendar 1980

TABLE II-1 HIPO STATUS SHOWING COMPLETED ITEMS

At RRI, simulated data corresponding to point-mass, zero-drag motion in a central inverse-square force field was used extensively early in the year to analyze filter performance and, as a result, to find and eliminate anomalies. The explanation of initially questionable trends in (forward) estimator covariance was eventually found in aspect angle effects at low altitudes, and in the initial effects of (zero) drag uncertainty at higher altitudes. Also, estimation residuals were materially reduced (and brought into consistency with optimal covariances) when effects due to non-linearity in the measurement model were identified and the sequence of processing radar measurements was changed from R, E, A to A, E, R.

Also, a case corresponding to one-dimensional particle motion along a straight line, with constant drag parameter, was formulated and solved to achieve analytic expressions for the covariance matrix elements. These results were used, in conjunction with the previous simulation, to achieve considerable confidence in the filter covariances and in very large allied sections of the equations and the system and measurements models.

Third, simulated input data corresponding to a known ballistic coefficient profile are being used in analyzing smoother algorithms, where the assumption of non-zero process noise is vital.

Finally, detailed hand calculations have been performed by RRI down to the individual subroutine level for the HIPO which has been delivered to MIT/LL. These calculations provide a valuable resource which can be useful in establishing confidence in detailed LODE calculations after subroutine-by-subroutine comparison between MIT/LL and RRI results.

E. TECHNICAL AND SOFTWARE LIAISON

During the contract year liaison among RRI, MIT/LL, and Ford-Aerospace was achieved through periodic (approximately monthly) project review meetings, supplemented by smaller working meetings at more frequent intervals as necessary. Typically,

the delivery of HIPO was accompanied with a session devoted to a detailed walk-through by RRI of the new HIPO, plus the resolution of any questions for the previous HIPO. Topics which have formed the subjects of specific meetings include:

1. discussion of HIPO for processing Multistatic Measurement System data,
2. RRI recommendations for creation of source of six degree-of-freedom (6 DOF) simulated data at MIT/LL,
3. use of already delivered rigid body HIPO as a kernel for the MIT/LL six degree-of-freedom simulator,
4. explanation of equations in card decks providing new covariance propagation equations to MIT/LL.

F. LODE PERFORMANCE EVALUATION

Evaluation of the performance of the LODE system with respect to such factors as accuracy, convergence, input parameter selection, aerodynamic modeling, measurement noise and sensor selection, assumed process noise parameters, and run iteration procedure is contingent upon running the system as a whole. However, that was not achieved for an entire trajectory during the contract year.

Nevertheless, examination of specific subsystem behavior (e.g., forward filter) was possible, as well as observation of entire system behavior over restricted regimes (e.g., exo-atmospheric with zero process noise), and qualitatively encouraging results and expected behavior observed. The forward filter, for example, provides estimates which are consistent with the input data and shows covariances which decrease in close agreement with theory. Smoother estimates (with zero process noise) are compatible with the input estimates from the two filters, and have covariances which throughout the trajectory are smaller than both filter covariances (as expected).

Further quantitative performance evaluation has, however, been given lower priority until a properly working smoother can be certified.

III. STATUS SUMMARY

During the contract year RRI completed the preparation of equations for the full rigid-body general-aerodynamics LODE capability, and delivered complete instructions for programming the full capability with quasi-symmetric vehicle aerodynamics. Augmentation of these instructions for programming, to include the general aerodynamics package, is planned for calendar year 1980. Both point-mass and rigid-body codes have been produced at MIT/LL from the RRI instructions for programming and intensive code and equation debugging are now in progress for the simpler point-mass code. The tasks which now remain to be accomplished to achieve the 6 degree-of-freedom LODE capability, in addition to equation and code documentation, are shown in Figure III-1.

During preparation of this report, a three degree-of-freedom (3 DOF) LODE capability has been debugged to the point of generating complete forward and backward filter estimates and computing optimal smoothed estimates for metric data and ballistic coefficient throughout reentry. This marks completion of a major milestone, and further testing with lift forces and bias estimation may now proceed with the code already prepared. Also, as indicated in Figure II-1, simplified aerodynamic coefficient driver equations[10] have been delivered to MIT/LL to permit simulation of rigid-body aerodynamic motions and trajectories. The RRI task for preparing additional instructions for programming the general aerodynamics package has been in abeyance, as full RRI resources have been devoted to achieving the working point-mass solution and code already mentioned.

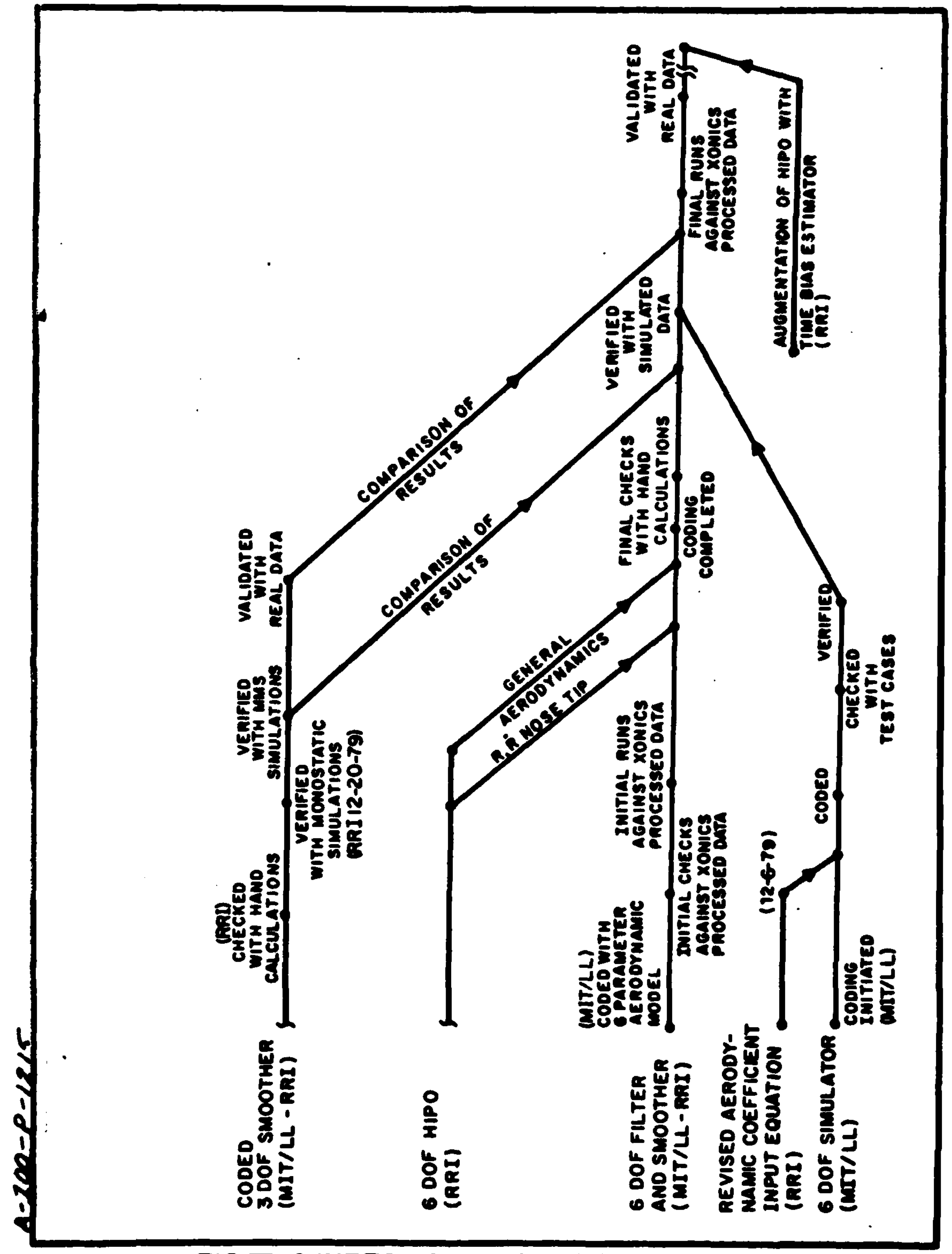


FIG. III -1 INTEGRATION OF RECENT ACTIVITIES

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